Formal Method for PSC Design Optimization of 13.56 MHz Resistive Wireless Analog Passive Sensors (rWAPS)*

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***Abstract* — Fully passive wireless body-worn sensors that collect physiological signals in natural settings is practical for seamless and unobtrusive monitoring of patients for medical cyber physical systems (CPS). In this regard, we have previously presented a novel Resistive Wireless Analog Passive Sensor (rWAPS), which is fully-passive, fast, low cost, and operates on the near field induction coupling method. Printed spiral coils (PSC) are one of the best solutions for near-field wireless communication for this fully-passive sensor. This paper describes a formal method to implement and optimize PSC coil pairs for such a system. Iterative process is required to reach optimal solutions of this complex multivariate optimization problem. After optimum design based on coil dimension, track size, and number of turns, a coil pair was fabricated on 2-layer PCB. The secondary coil size was restricted to a small footprint of 20mm, while the carrier frequency was selected as 13.56 MHz within ISM frequency band. Evaluation of the measurement from the prototypes and theoretically calculated results were found to be in agreement. This approach of PSC design optimization is practical for its application in our previously reported resistive transducer based wireless analog passive sensors (rWAPS) for body worn and wearable medical CPS.**

Index Terms— Wearable sensors, Body worn sensors, Fully passive sensors, Impedance loading, PSC, Iterative optimization, Medical CPS.

I. Introduction

Patient monitoring in the natural settings paves the path for better diagnosis, therapy and monitoring of medical cyber physical systems (CPS). Wireless connection between fully-passive (battery-less) sensors and interrogator removes the obtrusive wires and related complexity. Inductive coupling is a common way for wireless transferring of power and data [1]. We have previously presented a novel resistive based wireless analog passive sensor (rWAPS) [2,3], which is fast and requires very low power. For such a fully passive sensor design, the coil occupies most of the PCB floor plan. Therefore any attempt to reduce the size of the coil is valuable to reduce the sensor size. On the other hand reducing coil size also weakens the coil mutual connectivity and overall system loses its sensitivity to sense bio-signals. Printed Spiral Coil (PSC) based inductors are gaining attractions for wireless transfer applications due to their various advantages over conventional inductors such as low-cost, batch fabrication, durability, manufacturability on flexible substrates, etc. [1]. Having an efficient coil pair makes the backscattering or "load shift keying" possible in magnetic connection between scanner and sensor boards. In load modulation technique [4], load changing in the secondary is seen by primary via modulation. This method was applied to measure some bio-signals in our previous work with rWAPS [2,3]. This paper describes the optimization of the coil component only in terms of its size and mutual magnetic connection between coils. There are tradeoffs, for instance, if we try to increase mutual inductance by increasing the coil (conductor) length it increases the parasitic resistor that reduces the quality and decreases mutual inductance again. In [5-7], an iterative method is introduced and tested by measurement to design the optimum coil pair. Our effort here is focused on to implement this method to design a pair of PSC for rWAPS, and compare the test results with calculation.

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II. Input Constraints

For designing an optimum coil pair, some constraints have to be considered [8,9]. The constraints are those parameters that have limitations from size and fabrication. The four parameters in Fig. 1 are the general characteristics of a PSC. The constraints as the initial conditions for the iteration method are W_{min} and S_{min} (the PCB fabricator constraints), do_{Max} and d_{iMin} (the coil size restrictions). The restriction on W_{Min} and S_{Min} by the most PCB fabricators is 6 mils (152.4 μm). W is the input vector for the iteration and S is a single number.

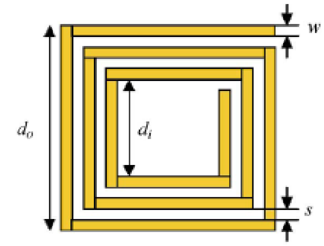

Fig. 1. Important characteristics of a PSC.

From Fig. 1, S should be chosen as small as possible and the vector of W starts from 6 mil. The outer dimension of PSC, d_O, has the restriction of the coil size specially, for the secondary that needs to be installed on the body and for the primary coil, depends on the application and the specific case, the maximum size is limited. For our implementation, d_{Omax} is limited to 40 mm for primary and 20 mm for secondary, and should be emphasized that the method will design the optimized coil with any inputs constraints, but the final and maximum efficiency depends on the limits and constraints (Table 1).

Table 1. The specific PSC design constraints in this optimization scheme.

Symbol	Parameter	Min	Max	Comment
W	Track width	6 mil	-	PCB fabricator Constraints W is the vector
S	Space between tracks	6 mil	-	PCB fabricator Constraints
d_{O1}	Primary Coil Outer dimension	-	40 mm	Application constraints Defined by designer
d_{O2}	Secondary Coil Outer dimension	20 mm		Application constraints Defined by designer
d_i	Coil Inner dimension	-	-	In some applications, it has minimum

III. Theoretical Formulas

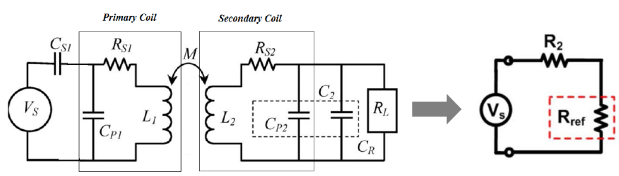

Fig. 2. The concept of reflected resistor from the secondary side to the primary side.

Firstly, the efficiency (η) is defined as [1]:

$$\eta = \frac{R_{ref}}{R_{ref} + R_2} \times \frac{Q_{2L}}{Q_L} = \frac{k^2 Q_1 Q_{2L}}{1 + k^2 Q_1 Q_{2L}} \times \frac{Q_2}{Q_2 + Q_L} \quad (1)$$

where:

$$R_{ref} = k^2 R_2 Q_1 Q_{2L} \quad (2)$$

Reflected resistor from secondary to primary (Fig. 2):

$$Q_1 = \frac{L_1 . \omega_0}{R_{S1}} \quad (3)$$

$$Q_2 = \frac{L_2 . \omega_0}{R_{S2}} \text{ (Quality without Load)} \quad (4)$$

$$Q_L = \frac{R_L}{L_2 . \omega_0} \times \frac{1}{\left(\frac{1}{Q^2} + 1\right)} \cong \frac{R_L}{L_2 . \omega_0} \quad (5)$$

$$Q_{2L} = \frac{Q_2 . Q_L}{Q_L + Q_2} \quad (6)$$

Equations (1)-(6) show that efficiency is a function of relevant quality factors (Q) that depend on a number of coil equivalent circuit parameters (Fig. 2). These parameters can be computed as follows:

Coil inductance:

$$L = \frac{1.27 n^2 4\pi \times 10^{-7} . (d_O + d_i)}{4} \left[\ln\left(\frac{2.07}{\varphi}\right) + 0.18\varphi + 0.13\varphi \right] \quad (7)$$

Parasitic series resistor:

$$R_S = \rho \frac{l_c}{w.t} \times \frac{t}{\delta . \left(1 - e^{-\frac{t_c}{\delta}}\right)} \quad (8)$$

$$\delta = \sqrt{\frac{\rho}{\pi \mu f}} \quad \text{(Skin effect)} \quad (9)$$

$$l_C = 4 n d_O - 4 n w - (2n - 1)^2 (s + w) \quad (10)$$

Parasitic capacitor:

$$C_P = C_{PC} + C_{PS} \approx (\alpha \varepsilon_{rc} + \beta \varepsilon_{rs}) \varepsilon_0 \frac{t_C}{S} l_g \quad (11)$$

$$l_g = 4(d_o - w.n)(n - 1) - 4s.n(n + 1) \quad (12)$$

And the last parameter that is to simplify the relation is called "fill-factor", and is defined as:

$$d_i = \frac{1 - \varphi}{1 + \varphi} d_o \quad (13)$$

Equations (7)-(13) show characteristics of a PSC. Therefore, these equations relate the signal transferring efficiency of the coil pair to the physical characteristics and the optimization is calculating the best physical characteristics and dimension to reach the maximum efficiency with considering the constraints.

IV. Iterative Method for Coil Optimization

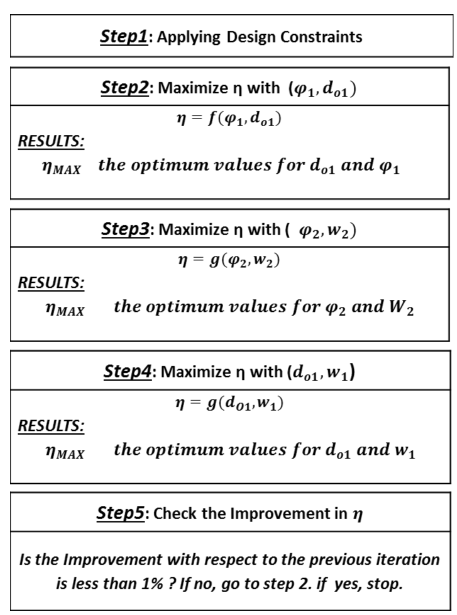

Fig. 3. The iterative procedure for coil optimization.

This implemented method maximizes the efficiency of signal transmitting from primary to secondary in five steps [5-7]. As the optimum value in each step has effect on the other steps, it has to be iteratively performed until having less than 1% (residual error) improvement in efficiency. Fig. 3 shows the summary of these steps. The computed result of efficiency optimization for the parameters in that iteration process is compared with the previous iteration result, and if the improvement is less than 1%, the iteration stops, otherwise iteration continues for another round.

V. Results

The constraints as outlined in Table 1 in conjugation of the constants input characteristics as shown in Table 2 are applied in MATLAB functions. The output results are shown in Table 3. The designed pair coils were fabricated (OshPark, PCB prototyping service) on a double layer PCB. The measurements were taken using Agilent 4294A Precision Impedance Analyzer (Agilent Technologies Inc., Santa Clara, CA). The measured values are compared against the formally calculated values as shown in Table 3.

Table 2. Input characteristics of PSC designing.

General Characteristics			
Parameter		Symbol	Design Value
Conductor Thickness		t_c	35.56* [μm]
Conductor Material Properties		ρ , μ_{rc}	1.7×10^{-8}, 1
Substrate Thickness		t_s	1.6 [mm]
Relative Dielectric Constant	Substrate (FR4)	ε_{rs}	4.4
	Coating (Air)	ε_{rc}	1
Empirical coefficients [1]		(α , β)	(0.9 , 0.1)
Nominal loading Resistor		R_L	1 KΩ
Coils Distance		D	
Carrier Frequency		f	13.56 [MHz]
Coupling Factor		K	0.07

*: referring PCB fabricator the conductor thickness is 1oz that is equal to 1.5mil

Table 3. Design results vs measurement values.

	Primary		Secondary	
Component	Calc.	Meas.	Calc.	Meas.
L (μH)	8.2	8.6	0.7	0.8
R_S (Ω)	3.6	5.2	0.6	0.7
C_P (pF)	7.5	4.5	1.1	1.3
C (pF)	9.3	11.5	196	171
d_O (mm)	40		20	
d_i (mm)	7.3		11	
φ	0.7		0.3	
w (mil)	20		20	
s (mil)	15		15	
n	19		6	
Q	227		103	
η	0.8			

VI. Discussion

As Table 3 depicts, for all the parameters the measured and calculated values agrees well. Even though the iterative process does not guarantee global maxima, but to sufficiently maximize efficiency, the local maximum must be reached. We note that for φ_2, it has value of 0.3 as the optimum value. To characterize the behavior of the efficiency with input parameters, the efficiency was analyzed over 3 inputs pairs as shown in Fig. 4 to Fig. 6.

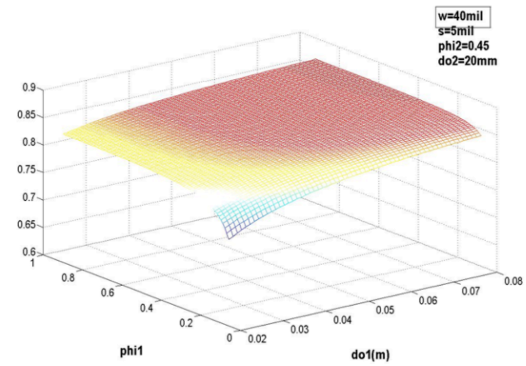

Fig. 4. The effect of phi_1 and d_{O1} on the η.

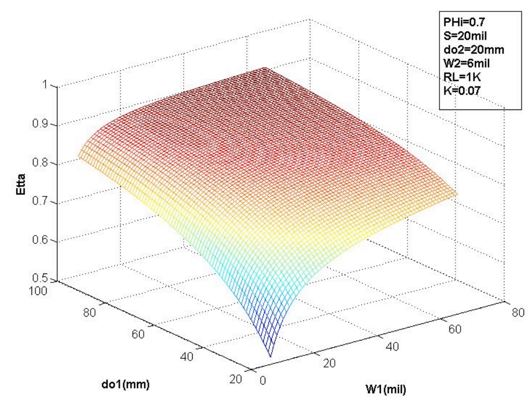

Fig. 5. The behavior of η with do1 and W1.

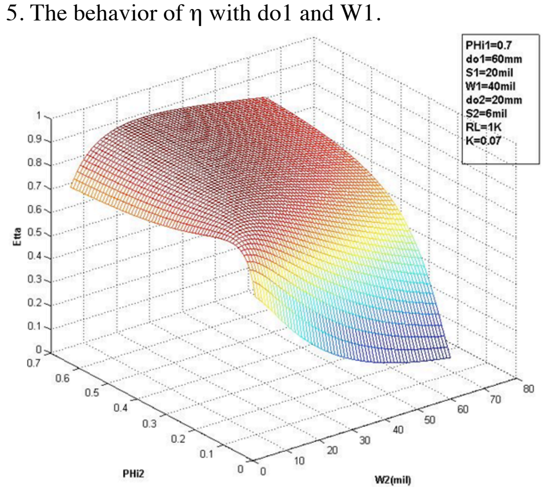

Fig. 6. The η versus w_2 and phi_2.

VII. Conclusion

This paper presents our attempt to implement PSC optimization based on the iterative method for rWAPS. The computed results are in close agreement with the measurement of fabricated PSC. Hence, it indicates that although the equations for equivalent components need to be modified to have better and more precise results, the results can still be very inspiring to design practical application of PSC. Optimal coil design will enable design of efficient fully-passive sensors that operate on inductive loading principle such as rWAPS for medical CPS applications.

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